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On the potential benefits of marine spatial planning for herring spawning conditions—An example from the western Baltic Sea

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ABSTRACT

Fisheries and marine spatial planning (MSP) still have a widely unsettled relationship. This paper reports on the potential benefits of MSP for the management of herring (*Clupea harengus* L.) stocks in the Greifswalder Bodden, a major spawning ground for western Baltic spring-spawning herring. The various pressures that have potential impacts on spawning conditions are identified based on a systematic literature review. Those anthropogenic activities that affect spawning conditions and could underlie MSP regulations are then analysed on the basis of the pressure maps to assess their importance for recruitment success in comparison to other pressures which are not subject to MSP by-laws, e.g. eutrophication. The results confirm that MSP could potentially improve the management of certain fish stocks and help to close existing gaps in European fisheries policy.

1. Introduction

The relationship between marine spatial planning (MSP) and fisheries in Europe has often been tension-fraught since the European Commission began promoting MSP in 2006. From the perspective of the fisheries sector, the initial attention often focused on competition for space and resources (Jentoft and Knol, 2014). Furthermore, MSP has been seen in part as another unwelcome regulation mechanism; this viewpoint has influenced the discussions between the fisheries communities and MSP authorities. In return, responsible MSP agencies often argued that fisheries are outside of their competence because of the Common Fisheries Policy (CFP). While several scientific studies highlighted the strong relation between fisheries and MSP (e.g. Gray et al., 2005; Crowder and Norse, 2008; Berkenhagen et al., 2010; van Deurs et al., 2012; Lamp, 2012), as well as ways in which fisheries could be included in MSP (e.g. Douvere et al., 2007; Fock, 2008; Stelzenmüller et al., 2008), so far fisheries are rarely considered in current marine spatial plans in Europe; exceptions are the Norwegian Integrated Management Plan for the Barents Sea-Lofoten area (Norwegian Ministry of the Environment (NME), 2011) and the English East Inshore and East Offshore Marine Plans (HM Government, 2012).

In contrast to the administrative reality, Worm et al. (2009) and Norse (2010) recommend ecosystem-based spatial planning to benefit marine fisheries. Current fishery management has shortcomings in considering the heterogeneity of fish populations and human uses (Norse, 2010) while MSP has a potential to support sustainable fisheries management by regulating anthropogenic activities. Within the CFP framework, fisheries management can only regulate the fisheries sector. Other variables, e.g. impacts of other anthropogenic activities on spawning conditions, are beyond the reach of the CFP, which has led to some criticism by the fisheries communities (Daw and Gray, 2005).

Numerous studies suggest that various anthropogenic activities have impacts on fish recruitment. For example, DeGroot (1979) reported a severe impact of sand and gravel extraction on sole recruitment, while Richardson (2003) summarised various studies on non-fisheries pressures on the recruitment of marine fish species, such as the impacts of eutrophication, introduction of non-indigenous species, contamination, and noise introduction. Sundby and Nakken (2008) highlighted the impact of climate change on Arcto-Norwegian cod spawning and Grabowski et al. (2012) suggested that even broadcast spawning fish, such as Atlantic cod *Gadus morhua*, may rely on specific spawning habitat types, and concluded that those areas should be protected from anthropogenic disturbance. Recruitment success might also be influenced by anthropogenic noise. Detailed studies on the effects of noise on recruitment are largely missing, but various studies have analysed

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general impacts, e.g. the avoidance of vessels by fish (Olsen, 1971, 1979; Olsen et al., 1983; Ona and Godø, 1990; Gerlotto and Fréon, 1992; De Robertis et al., 2010; De Robertis and Handegard, 2013). The noise emitted from vessels is in the acoustic range detected by fish (Engås et al., 1995; Mitson, 1995), and fish, including herring, react with evasion (Misund et al., 1996; Soria et al., 1996; Vabø et al., 2002; plus reviews in Fréon and Misund, 1999). Furthermore, the general alteration of marine ecosystems and the influence on fish stocks is highlighted by various studies (e.g. Lotze et al., 2006; Worm et al., 2006, 2009).

The present study analyses the potential of MSP to influence the spawning conditions of herring, *Clupea harengus* L., in the Greifswalder Bodden, a major spawning ground for western Baltic spring-spawning herring (WBSS). The paper starts with a short illustration of the study site, covering its environmental and economic characteristics. This is then followed by an explanation of the methodology and an account of the study findings. The paper concludes with a discussion of key issues raised by the exercise and the implications for more sophisticated and place-sensitive approaches to marine management.

2. Study site

With an area of 510 km^2, Greifswalder Bodden is the largest shallow bay within the south-western Baltic Sea. It is surrounded by the island of Rügen to the north and the mainland to the west and south (Fig. 1). The bay is connected to the Baltic Sea by a narrow and shallow sill and the Strelasund channel. Nutrient-rich riverine waters enter the bay via the Peene outlet and Strelasund channel. Sediments consist mainly of mud, with fractions of sand and clay-gravel mixture. Hydrodynamics are mainly driven by wind, with mixing leading to a generally well-oxygenated water column (Stigge, 1989; Munkes, 2005). However, stratification, especially during the spring and summer seasons, may lead to temporary

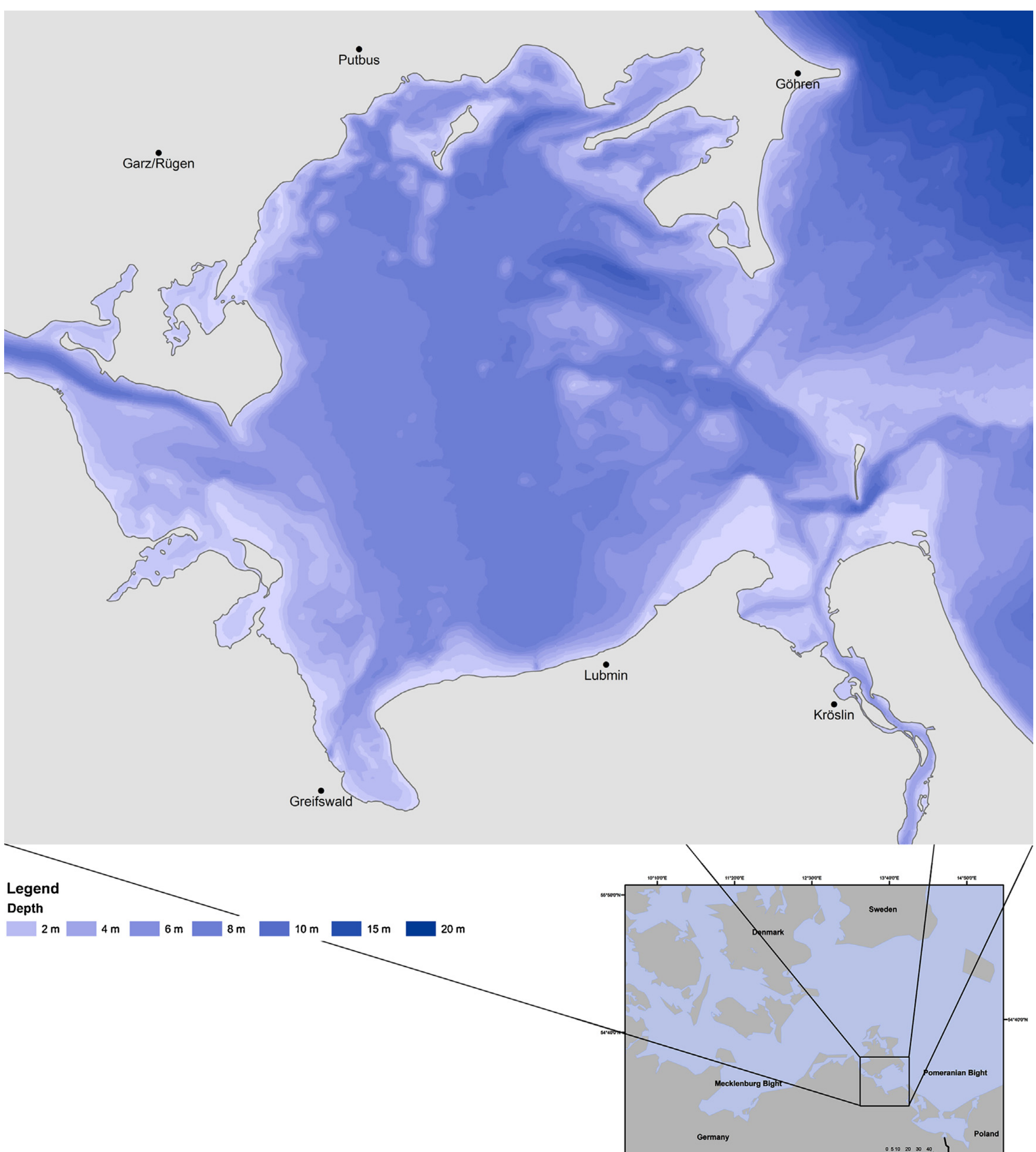

Fig. 1. Case study area 'Greifswalder Bodden'.

anoxia in bottom layers. The average water depth is around 5.8 m (max. 13.5 m). Wind-driven inflows via the eastward inlet lead to water retention times of 4–6 weeks (Stigge, 1989; Hubert et al., 1995; Lampe and Meyer, 1995). As a shallow body of water, Greifswalder Bodden is subject to higher temperature variability than adjacent marine waters.

With salinity values around 7 psu, Greifswalder Bodden is a brackish system characterised by a mixed marine and limnic fauna. These conditions attract a limited number of salinity-tolerant species, including herring, *C. harengus* L. The Greifswalder Bodden is a major spawning ground for WBSS herring. Approximately 80% of WBSS stocks are spawned in Greifswalder Bodden and the adjacent Strelasund (ICES, 1998). The main spawning season is between March and May (Scabell, unpublished; von Dorrien et al., 2013). WBSS is a substrate spawner and requires mainly aquatic vegetation, e.g. macrophytes, as substrate (Biester, 1979). Therefore, spawning focuses on vegetated near-shore zones. As these zones are under manifold anthropogenic pressures, the reproduction success of WBSS is highly vulnerable to human-induced habitat alteration (von Dorrien et al., 2013).

Greifswalder Bodden is protected under various environmental protection schemes. In addition to national regulations (it is partly protected as a nature reserve and as fish and spawning preserve areas with temporary angling prohibition), it is protected under European Natura2000 law and fully covered with protection areas under the European Birds Directive (SPA) and the Habitat Directive. Furthermore, north-eastern parts of Greifswalder Bodden belong to a UNESCO biosphere reserve. At the same time, Greifswalder Bodden experiences a broad range of anthropogenic activities. Aside from fisheries, the bay is used mainly for tourism, leisure, and maritime transport. Shoreline modifications, ports and marinas, sediment extraction and dumping, installations of energy infrastructure (cables, gas pipelines), noise and light emissions, fishing, coastal tourism and industries, as well as eutrophication lead to multiple pressures on the bay (Janßen et al., 2013).

An MSP plan for Greifswalder Bodden and adjacent areas has existed since 2005 (AM-MV (Ministerium für Arbeit, Bau und Landesentwicklung Mecklenburg-Vorpommern), 2005). In addition to the previously-mentioned legislation, the existing MSP plan specifies the bay as an area reserved for both tourism and nature conservation, with single coastal spots designated as priority areas for nature conservation. A small part of the bay is reserved for cables and pipelines. Further MSP regulations do not currently exist. The amount regulation in the existing MSP plan is not large, with multiple activities or functions having equal rights. In addition to the official MSP plan, a group of water sport associations made a voluntary agreement with a nature conservation organisation to avoid shipping and canoeing in selected shallow nearshore areas. This concept has been partly taken up in the draft of an upcoming update of the MSP plan (Ministerium für Energie, Infrastruktur und Landesentwicklung Mecklenburg-Vorpommern (MEIL-MV), 2014a) which reserves certain areas for fisheries. This regulation seeks to protect fisheries resources (e.g. presumed spawning areas) from disturbances.

3. Methodology

In formulating a suitable methodology for the analysis of the potential that MSP has to influence the spawning conditions for herring in the case study, an initial conceptualisation of the purpose and scope of the analysis was undertaken. Based on the ecosystem approach, the analysis should

- reflect complex interactions between human activity and the environment, including those between the land and sea;
- consider potential impacts during different life and development stages of herring, i.e. on adult spawners and on spawning conditions; and
- draw upon all forms of relevant information.

With this in mind, it was established that the analyses should draw together as comprehensively as possible information on the potential impacts of anthropogenic activities on herring spawners and spawning conditions, regardless of whether they are subject to regulations by MSP. For this purpose, a stepped approach was adopted, building from literature studies to single data sets, which were then aggregated into cumulative pressure maps to produce an overall synthesis of the data and an analysis of MSP-relevant drivers and pressures. The steps were as follows:

3.1. Literature studies

Literature studies of anthropogenic impacts on (a) adult herring, and (b) spawning substrate for WBSS herring, especially macrophytes and other suited aquatic vegetation, laid the basis for later analysis. Articles published from 1965 to 2013 were selected by means of a structured literature search in SciVerse (ScienceDirect & Scopus), Web of Science, Google Scholar, and OCLC WorldCat. Supplementary papers were found by following the references of articles found in the above-mentioned databases and search engines. Search words for (a) were combinations of "baltic", "herring", "*C. harengus* L.", "pressures", "disturbance", and "impacts"; and for (b) combinations of "western Baltic", "spring spawn", "substrate", "*Zostera marina*", "seagrass", "*Potamogeton pectinatus*", "fennel pondweed", "*Ulva*", "green algae", "*Furcellara fastigiata*", "black carrageen", "*Polysiphonia nigrescens*", "red algae", "*Fucus vesiculosus*", "bladderwrack", "pressures", "disturbance", and "impacts". Studies were included if they dealt with impacts originating from anthropogenic activities on either (a) or (b), and if they were written in English or German.

From the selected studies, qualitative and, as far as available, quantitative data on the sensitivity of (a) and (b) against the respective pressure were extracted. These data were used to calculate pressure maps (step 3).

3.2. Data sets on anthropogenic activities

Based on the identification of drivers and pressures through the literature studies, spatially-explicit data sets on anthropogenic activities, as well as on abiotic and biotic variables, were collected from different sources (cf. step 3). Suitable data sets were selected on the following criteria:

1. The data sets had to be validated (e.g. no non-validated model data), scientifically reliable (e.g. peer-reviewed) and come from a trustworthy source (e.g. public authorities, scientific databases).
2. Data sets had to cover the case study region as a whole and needed to be sufficiently detailed: i.e. in the case of measured data, the case study region had to be covered by at least five sampling points.
3. The various data sets had to be up-to-date and, as far as possible, give data for the same time span.

All data sets represent the situation in the years 2010 to 2012, and were accessed by national authorities (State Agencies for Agriculture and Environment; Mining Authority Stralsund; Federal Maritime and Hydrographic Agency; Water and Shipping Authority Stralsund; States Agency for the Environment, Nature Conservation and Geology) or public and private research institutes (Thünen Institute of Baltic Sea Fisheries; Institute for Applied Ecology).

3.3. Calculation of spatial pressure indices

Having identified suitable data sets and, where not already present, transformed the data sets into maps, two spatial pressure indices were developed to aggregate anthropogenic stress on (a) adult herring (spawners) and (b) spawning substrate or WBSS herring. Where necessary, this step entailed the development of normalised values for each data layer to enable aggregation of data. The method follows Halpern et al. (2008) and Janßen et al. (2013). For both indices, index scores for direct and indirect anthropogenic uses and interests in the seas were calculated as follows:

$$I = \sum_{i=1}^{n} (a_{it}) \qquad (1)$$

where a is a normalised value for anthropogenic pressures at location i at season t. To include the temporal dimension of anthropogenic activities, each index was calculated separately for each of the four seasons (spring: March, April and May, MAM; summer: June, July and August, JJA; autumn: September, October and November, SON; winter: December, January and February, DJF). The pressures represented by the variable a were given values between 0 and 4, with 4 indicating intensities that may cause the highest expectable impact (i.e. a habitat is completely destroyed) and 0 representing a situation without any impact. Variable a was normalised by $x' = \lambda x$, where λ is a scaling factor of variable magnitude for the respective anthropogenic activity. Those pressures that may directly affect an entire area received a scaling factor of 1 (no scaling), e.g. dredging and sealing activities. Pressures that affect only single parts or elements were downscaled with scaling factors between 0.2 and 0.6 (e.g. anchorage areas where only part of the area is impacted by noise emissions or physical damage from anchors). These scaling factors balanced variation in the spatial resolutions of the different data sets to avoid giving rise to higher theoretical pressure values for spatially limited pressures within coarse data sets than actually occurred. In turn, small-scale peak values were reduced, as they were averaged over space, depending on the spatial resolution of a data set. The spatial pressure indices are intended to identify fields of action in MSP; they are not meant to calculate cumulative impacts. The normalisation procedure therefore only balances pressures based on their spatial extent, and does not normalise the different mechanisms of pressure. Each normalisation procedure was used to adjust only the values within the respective index; the scales of the two indices on (a) and (b) are thus different and the indices are not suited for direct comparison.

Each of the two indices on (a) and (b) were calculated as digital maps and, in the case of the pressure index on spawning substrate, validated using observation data on the spatial distribution of spawning substrate (Hammer et al., 2009) by overlay analysis in a geographic information system (GIS). An overview of the pressures identified in step 1 (literature study) is given in Table 1.

This listing is missing certain anthropogenic pressures that should ideally be included in this type of analysis. For example, reliable data on the release and distribution of pollutants or toxic exudates were not available. Catch of herring by fisheries or angling was not included due to methodological difficulties in the calculation of a pressure value (e.g. share of spawners caught before spawning).

In principle, macrophytes, a spawning substrate for WBSS herring, may both suffer and benefit from anthropogenic activities, e.g. by the creation of additional hard substrates (Qvarfordt et al., 2006). However, under the current conditions, this effect may be very limited, as eutrophication and limited light availability set substantial restrictions on the dispersal of macrophytes (Kautsky et al., 1986; Malm et al., 2001; Domin et al., 2004).

Table 1
Selected anthropogenic pressures on spawning conditions of WBSS herring.

Pressures on *Clupea harengus* L. during different life stages (in brackets: effect)	Pressures on spawning substrate for WBSS herring (in brackets: effect)
Eutrophication (turbidity)	Eutrophication (turbidity, displacement)
Construction (behavioural changes, coverage)	Dumping areas (coverage)
Dredging, mineral extraction (turbidity, coverage)	Sealing (physical damage)
Dumping (coverage)	Dredging (physical damage)
Maritime transport (behavioural changes)	Anchorage (physical damage)
Bathing (behavioural changes)	Maritime transport (physical damage)
Yachting (behavioural changes)	Grounding gillnets (physical damage)
Surfing (behavioural changes)	Bow nets (physical damage)
Canoeing (behavioural changes)	

3.4. Analysis

In the final stage, the potential pressures of anthropogenic activities on herring spawning conditions were analysed on the basis of two pressure indices maps. In addition, the potential benefits of MSP for herring spawning conditions were deduced by an examination of the potential of MSP to regulate the identified pressures under consideration of their proportional impact on spawning conditions.

4. Results

The two literature searches led to more than 700 results with general relevance to the topic. Of these, 84 studies had higher significance for the Greifswalder Bodden. These are studies in comparable ecosystems or studies on similar anthropogenic stressors. Twenty-six of those 84 studies were selected to assess the influence of various anthropogenic activities on herring and spawning substrate for WBSS herring. The other documents contained results of congeneric studies which were repeated at different case studies. The selected papers thus represent further studies with comparable results. The overall knowledge base on anthropogenic impacts on herring and WBSS herring spawning substrate for the given case study is substantial and the literature studies provided sufficient data for the following assessment.

4.1. Direct anthropogenic pressures on Baltic herring (Clupea harengus L.)

Blaxter (1965) stresses the importance of vision in the early stages of herring for success and failure in feeding (Table 2). Turbidity caused by eutrophication and suspended sediment decreases light availability, impacting feeding success of herring larvae (Johnston and Wildish, 1982; Fox et al., 1999). Reduced light availability also affects the vision and behaviour of adult herring. Reduced light intensity may influence the ability of herring to shoal in groups and to recognise nets (Blaxter and Parrish, 1965). Another effect of eutrophication is linked to toxic exudates released by filamentous brown algae, which are favoured by eutrophication and may cause an increase in herring egg mortality (Aneer, 1987).

Spillage over herring eggs as caused for instance by dredging or dumping may negatively affect oxygen uptake, with subsequent impact on the development of eggs (Braum, 1973). However, Kiørboe et al. (1981) stated that spillage with suspended silt does not influence the embryonic development of herring; their study approach was criticised by von Dorrien et al. (2013).

Table 2
Potential impacts of selected anthropogenic pressures on adult herring (*Clupea harengus* L.).

Effect	Life stage	Impact	Reference/source	Cause/pressure
Turbidity	Larvae	Reduced feeding/hunting success	Blaxter (1965), Johnston and Wildish (1982), Fox et al. (1999)	Nutrient emission, construction works if sediment is touched
	Adult	Effects on shoaling	Blaxter and Parrish (1965)	
Spillage	Eggs	Effects on oxygen uptake, deformation	Braum (1973)	Dredging, sediment extraction, dumping, construction if sediment is touched
	Eggs	No correlation	Kiørboe et al. (1981)	
	Eggs	Criticism on Kiørboe	von Dorrien et al. (2013)	
Pollutant emission	Eggs	Impaired gas exchange	Rosenthal (1971)	(Not considered)
	Embryo	Deformation	von Westernhagen (1988)	(Not considered)
	Eggs and larvae	Death	von Westernhagen et al. (1979)	(Not considered)
		Deformation	Somasundaram et al. (1984)	(Not considered)
	Eggs	Reduced number of eggs up to 80%	von Westernhagen (1988)	(Not considered)
	Larvae	Deformation, Death	Lindén (1978)	(Not considered)
Noise	Adult	Behavioural change	Wahlberg and Westerberg (2005), Nedwell et al. (2003), Popper and Hastings (2009)	Shipping, bathing, coastal industry, leisure sports (yachting, surfing, canoeing)
Eutrophication	Eggs	Negatively effects caused by toxic exudates released by filamentous brown algae	Aneer (1987)	(Not considered)

Pollutants may have severe impacts on herring at various life stages. von Westernhagen (1988) reviewed the non-lethal effects of a wide range of pollutants on early stages of herring and reported a strong reduction in the number of eggs and deformation of larvae. Negative combined effects of cadmium, copper and lead on embryonic survival were identified by von Westernhagen et al. (1979). Rosenthal (1971) detected impaired gas exchange in herring eggs, resulting in significantly increased mortality and deformation, caused by arsenic red mud. Deformation and death of herring larvae caused by hydrocarbons were shown by Lindén (1978). Despite the fact that pollutants may have serious impacts on herring, they were not included in the pressure assessments. The release of pollutants is directly linked to anthropogenic activities, but reliable data on the on-going release and distribution of pollutants caused by current activities were not available. Therefore, pollutants were excluded from further analyses to avoid speculative estimates.

There is little peer-reviewed literature on the effects of anthropogenic noise on herring or on fish in general. Popper and Hastings (2009) reviewed the literature and stated that existing studies concordantly report avoidance reactions and behavioural changes. However, noise may not necessarily keep herring away from their spawning grounds. As shown by Weber (1971) and Aneer (1989), WBSS herring also seek their spawning grounds in the Kiel Canal, one of the most heavily used artificial seaways in the world (Janßen et al., 2013). To what extent noise affects the health of herring is not well researched, but because of the avoidance reactions, noise introduced by maritime traffic, leisure activities and construction was considered mild stress in this study.

4.2. Anthropogenic pressures on WBSS spawning substrate

Western Baltic spring spawning (WBSS) herring spawn predominantly on aquatic vegetation, with very few exceptions (Klinkhardt and Biester, 1985; Kääriä et al., 1988; Rajasilta et al., 1993). This focus on shallow vegetated near-shore zones for spawning causes reproduction success to be intensively influenced by human activities such as dredging, sealing, riverine inputs, etc. This situation has worsened over the past few decades as eutrophication and the subsequent reduction in the photic zone has led to a decrease in the number of vegetated spawning areas in Greifswalder Bodden (Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern (LUNG), 2008; von Dorrien et al., 2013). Sagert et al. (2005) reported that *Z. marina*'s depth limits are significantly negatively correlated with concentrations of total nitrogen, total phosphorus and chlorophyll a, as well as with *Myrionecta rubra* biomass, and strongly positively correlated with Secchi depth (Table 3). Further studies highlighted that eutrophication leads to displacement and habitat alteration of macrophytes (Lindner, 1978; Pilz, unpublished, cf. von Dorrien et al., 2013), e.g. by leading to high concentrations of competing filamentous algae (Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern (LUNG), 2008).

Dredging and dumping, as well as various types of construction within the marine environment, may lead to the release of suspended matter, plumes of suspended sediments and subsequent sedimentation. Shoreline modifications may lead to sediment transport patterns, resulting in sediment accumulation along the adjacent coast. These processes may cause not only temporary turbidity but also permanent burial of seagrass and other macrophyte beds, leading to decreased productivity and increased mortality of spawning vegetation (Mills and Fonseca, 2003; Tu Do et al., 2012) and to a reduced number of spawning grounds (Kääriä et al., 1988; Rajasilta et al., 1993).

Various studies highlighted that other kinds of physical damage, such as removal of macrophytes by the uplift of anchors, sealing of preferred settling substrates, and direct impacts by boat propellers, may also cause a decline in macrophyte stocks (e.g. Walker et al., 1989; Francour et al., 1999; Borum et al., 2004; Okudan et al., 2011). The main drivers behind this type of impacts are the increasing human use of the coastal zone for transportation, recreation and food production.

4.3. Seasonal cumulative impact maps for Baltic herring (Clupea harengus *L.)*

The literature studies contained heterogeneous information on impact intensities. These were homogenised (see Section 3.3) to calculate indices on potential cumulative impacts. Fig. 2 shows the cumulative potential impacts of direct anthropogenic pressures on *C. harengus* L. as depicted in Table 2. It is immediately clear that impact intensity changes with season. The winter quarter (DJF) shows very low potential impact values, while the summer season (JJA) shows clearly intensified values, especially for shallow coastal areas. During spring (MAM) the cumulative potential impact intensifies in nearly all parts of the Greifswalder Bodden, with an average cumulative value of 2 and a maximum value of 6. The main causes are increasing impacts of eutrophication (Table 2), intensified tourism and water sports. This trend continues during the summer months (JJA). Then most of the bay remains in a situation with little direct anthropogenic stress affecting adult herring (cumulative potential impact value: 2), but in single smaller coastal areas, especially along the southern and northern shorelines, the

Table 3
Potential impacts of selected anthropogenic pressures on WBSS herring spawning substrate.

Effect	Impact	Source	Cause/pressure
Turbidity	Limiting photic zone, drastic effect on spawning substrate	von Dorrien et al. (2013), Sagert et al. (2005)	Nutrient emission, construction if sediment is touched
Sedimentation of suspended matter	Reducing potential spawning grounds	Kääriä et al. (1988), Rajasilta et al. (2006)	Dumping areas, dredging, construction if sediment is touched
	Seagrass bed burial	Tu Do et al. (2012)	
	Mortality, decreased productivity	Mills and Fonseca (2003)	
Pollutant emission	Inhibited growth	Lyngby and Brix (1984)	(Not considered)
Eutrophication	Reduction of macrophytes habitats	von Dorrien et al. (2013)	Nutrient emission
	Macrophytes displaced by algae	Pilz (unpublished; cf. ibid.)	
	Macrophytes habitat alteration	Lindner (1978)	
	Overgrow of macrophytes by green algae	Landesamt für Umwelt, Naturschutz und Geologie Mecklenburg-Vorpommern (LUNG) (2008)	
Physical damage	Decline, removal, sealing	Borum et al. (2004)	Dredging anchorage ship propellers grounding gillnets Bow nets sealing/construction sites

intensity of cumulative potential impacts increases and reaches a maximum of 10. This value indicates that three or more human activities have reached a high intensity that will lead to an avoidance reaction by *C. harengus* L, as outlined in Section 4.1. In the autumn (SON), human activities in, on and around the bay decline in intensity, with pressure intensities similar to the spring season.

Nearly all of those coastal areas with high potential impact values during the summer are located either directly within or in the direct vicinity of macrophyte areas and are therefore potential spawning grounds. This will not affect the migration of spawners to or from the spawning grounds, as spawning happens from January to April and spawners leave the area within a few days after completing spawning (Biester et al., 1978).

4.4. Seasonal cumulative impact maps for WBSS herring spawning substrate

Fig. 3 shows the seasonal cumulative potential impact of anthropogenic pressures on WBSS herring spawning substrate. At a first glance it is clear that seasonal differences are not as distinct as in Fig. 2, which showed potential impacts on adult herring. The black crosshatch, which covers large parts of the bay, indicates those areas where light penetration and vertical range of the euphotic zone is not sufficient for permanent growth of ellgrass *Z. marina* (cf. Greve and Krause-Jensen, 2005; Munkes, 2005). This situation is caused mainly by eutrophication and high nutrient inputs into coastal waters. As a consequence, phytoplankton concentrations and suspended solids increase, leading to a substantial decrease in light availability at bottom layers and a phase shift from a macrophyte-dominated to a phytoplankton-dominated ecosystem (Munkes, 2005). In the given case, data on Secchi depth was taken from the regular coastal monitoring (year 2010) and interpolated across the Greifswalder Bodden. According to these data, 93.5% of the bay area was so turbid during the spring months (MAM) that *Z. marina* would not have been able to grow there (hatched area). Turbidity values were 95.7% for summer (JJA) and 94.0%. for autumn (SON). For this study, it was assumed that these values are valid also for other macrophytes used by WBSS herring for spawning activities.

Within the remaining areas, the disturbance of potentially vegetated spawning areas by anthropogenic pressures on macrophytes is mostly low during the winter (DJF), spring (MAM) and autumn (SON). Within summer months (JJA), about one quarter (25.5%) of those areas which are subject to sufficient light penetration show cumulative potential impact values above 1.0, indicating a mild temporal stress on the vegetation. During summer, only 6.2% of those areas with sufficient light availability achieve cumulative potential impact values above 1.9. In both cases, tourism, water sports, bathing and other types of leisure or recreational activities are the main driving forces.

These results do not mean that those human activities which could potentially directly destroy vegetated spawning grounds (e.g. dredging) would not occur within Greifswalder Bodden. Rather, eutrophication, which causes the overall dominant impact of turbidity, and physical and other damage are hidden behind this predominant pressure.

5. Discussion

The results of this study show that, in principle, MSP can provide a valuable contribution to the management of fish stocks. Many of the pressures identified by the literature review and listed in Tables 2 and 3 are subject to MSP regulations. Activities such as coastal and maritime construction, sediment extraction, dredging, dumping, maritime transport, and leisure activities can be regulated by MSP (cf. Douvere, 2008; Jay and Gee, 2014). This includes regulations regarding space, time and intensity. The full potential of MSP as a supporting regulatory tool for the management of herring stocks is currently not being used. So far, a holistic management of spawning grounds is lacking, as is the regulation of pressures on recruitment conditions by human activities in these areas. Some sectoral directives, for example the national fisheries by-law, try to protect spawning conditions by regulating single sectors, while many other activities with a potential impact on WBSS herring recruitment success remain unregulated in terms of their influence on spawning conditions. MSP has the necessary legal and administrative capacity to control the intensities as well as the temporal and spatial dimensions of those human activities and could provide a benefit to the management of fish stocks.

The example of Greifswalder Bodden, however, also shows some of the limitations of MSP in contributing to a sound fisheries management. In the Greifswalder Bodden, the predominating pressure is eutrophication. The impact of eutrophication on spawning conditions is so strong that under current conditions, any improvements caused by MSP measures would be barely noticeable. Eutrophication has caused the bay to lose most of its spawning vegetation in recent decades, and the eutrophication problem needs to be solved before MSP can yield its full potential. Nonetheless, MSP can provide a sound management of those 4–7% of the bay area that is potentially suited as spawning grounds by protecting them from additional disturbances, especially from physical damage and noise or pollutant emitting activities.

MSP also has limitations related to impacts of pollutants on WBSS herring. These impacts are mostly outside of the regulatory

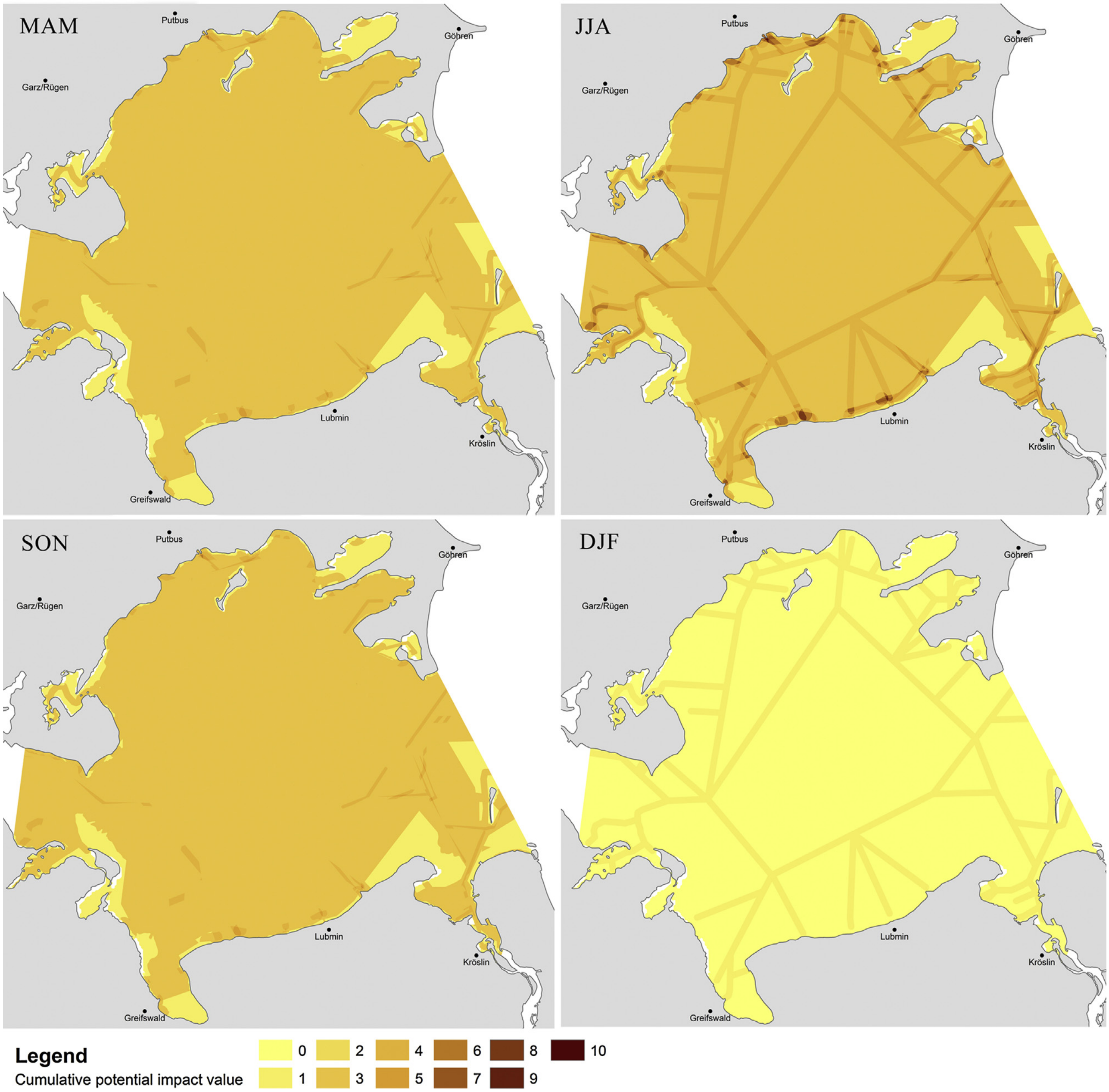

Fig. 2. Cumulative potential impact index of anthropogenic pressures (see Table 2) with impacts on adult herring (*Clupea harengus* L.). *Note*: WBSS herring typically enter the bay from January to April (see Section 4.3). Further months are displayed for the sake of completeness only.

competences of MSP and were therefore excluded in this study. von Dorrien et al. (2013) reviewed the existing literature on WBSS herring, demonstrating that this has been widely researched, and identified various stressors with impacts on WBSS herring. That study found that, in particular, pollutants may have strong effects on herring development. Even if MSP is a broad and holistic tool, it may not be the right instrument to reduce all pressures. As always, holistic management concepts like MSP need to be complemented by sectoral regulations.

MSP regulations on spawning sites do not necessarily have to be year-round exclusionary orders. As revealed above, there is a strong seasonal component to spawning activities and the anthropogenic pressures on them. Temporal regulations would be a sensible way to safeguard sound spawning conditions while allowing a sustainable development of further economic sectors. At the same time, special attention should be paid to the spawning vegetation that is vulnerable during all seasons, which is currently clearly in need of protection if the Greifswalder Bodden is to keep its function as an important spawning ground for WBSS herring.

That it is feasible to integrate aspects of fisheries management in MSP is shown by the upcoming MSP plan of Mecklenburg-Vorpommern (Ministerium für Energie, Infrastruktur und Landesentwicklung Mecklenburg-Vorpommern (MEIL-MV), 2014b). The current draft, which shall come into force by the year 2016, includes spawning grounds within and outside of the Greifswalder Bodden. Based on an assessment of potential spawning and nursery grounds, a number of areas mainly along coastal zones of the Greifswalder Bodden, its inlet towards the Pomeranian Bight, and around the island of Rügen have been marked with the legal status of a “restricted area for the protection of fisheries resources”. According to the applicable German Spatial Planning Act, this means that the safeguarding of spawning conditions is

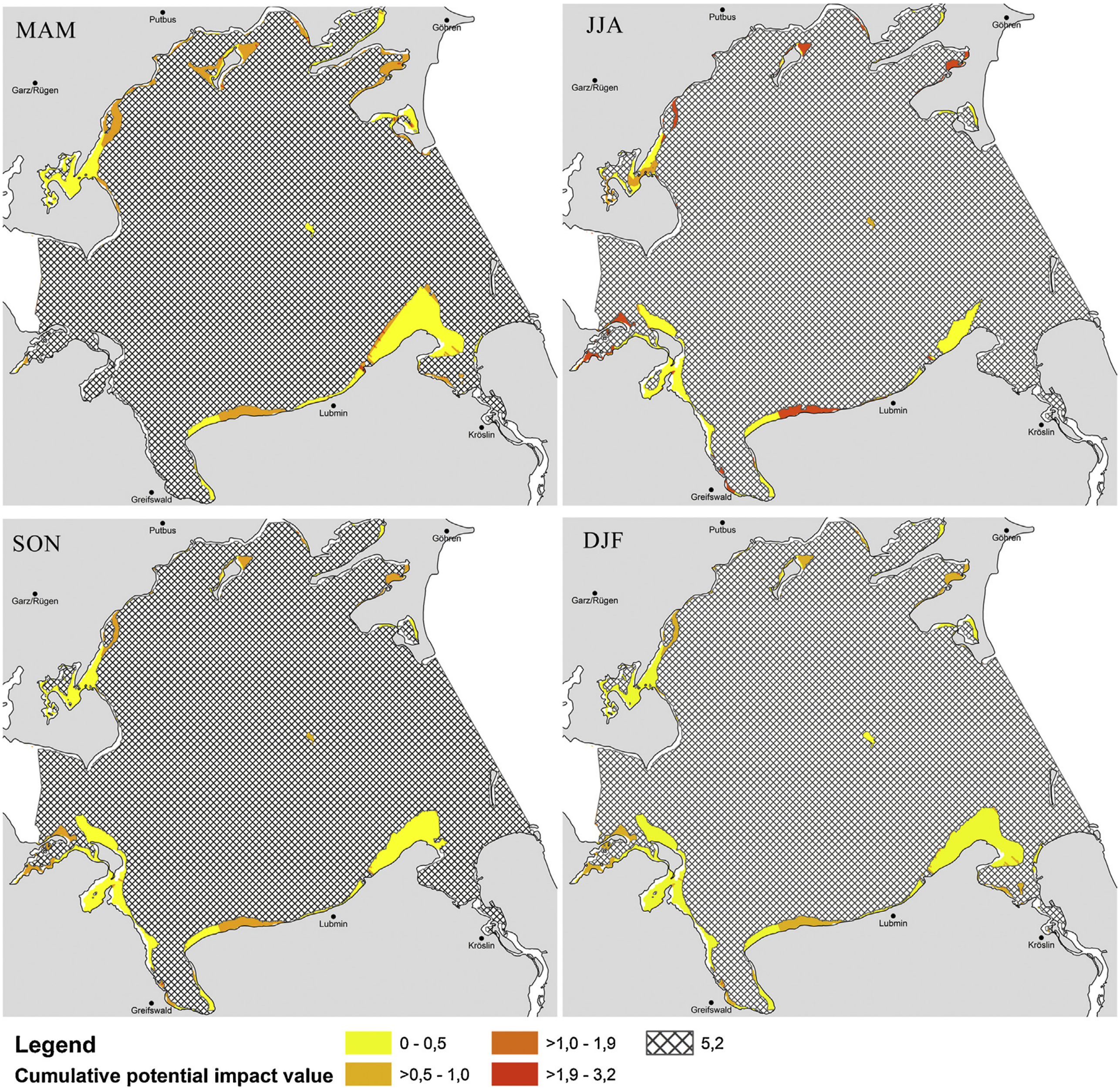

Fig. 3. Cumulative potential impact index of anthropogenic pressures (see Table 3) with impacts on vegetated spawning substrate.

given particular weight in comparison to other competing uses: i.e. if another competing use claims interest in the same area, then that interest has to be treated with lower priority in the decision-making process. This does not exclude other uses from spawning grounds, even if they are potentially harmful to spawning activities. But these other uses need to prove a strong societal interest if they want to obtain approval in a restricted area.

Within Europe, the MSP plan of Mecklenburg-Vorpommern will be one of the first examples of the integration of spawning activities in MSP. For the stock development of species that rely on certain spawning grounds, as WBSS herring do, it would be helpful if MSP could try more often to integrate scientific knowledge on the management of ecosystem components.

Norse (2010) stated further potential benefits of MSP for fisheries beyond the above-given example for spawning conditions. He claimed that "fishermen who work intensively within a defined area [. . .] are much more likely to fish sustainably." This, however, would require not only sound – and, for single fisherman, economically sufficient – fish stocks within those zoned fishing areas, but also more discerning thinking about the spatial needs of fisheries (e.g. the role of mobility in fishing, connectivity, and distances between ports and fishing areas). Within EBM approaches to fisheries, these issues have partly been researched. But more research in this direction will be necessary to enable authorities to fully include fisheries in MSP processes.

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